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Original Research

Suitable Scale of Oases in Arid Regions: a Case Study of the Middle Reaches of the Heihe River Basin, China

Xia Tang[1,2*], Sen Li[1]

[1]Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[2]Key Laboratory of Ecohydrology of Inland River Basin, Chinese Academy of Science, Lanzhou 730000 China

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Abstract

Assessment of the suitable scale of oases is an effective way to efficiently and rationally allocate water resources in arid areas. In this study, a suitable oasis scale computation model was adopted based on water-heat balance theory to assess the changes in the scale of oases within the middle reaches of the Heihe River Basin (HRB) located in northwestern China. The results show that the runoff of the HRB was characterized by obviously plentiful and withered periods from 1954 to 2015. Under the premise of ensuring the downstream ecological water utilization target, the suitable scale of oases was 3222-4832 km^2, 2583-3875 km^2 and 2221-3332 km^2 in high-flow, normal-flow and low-flow years, respectively. The status quo of 2015 far exceeded the suitable scale of oases that could be supported by the water resources in the basin in normal-flow and low-flow years, and the suitability index of the oasis scale declined to 0.44-0.59. To ensure the stability of the oasis system, controlling the scale of oases as much as possible within the range of areas that can be supported by water resources is necessary, as is analyzing in depth the suitable proportions of arable land, grassland, and woodland in the future to establish a multi-benefit oasis ecology protection system, thereby providing guidance for the sustainable development of oases in arid areas.

Keywords: different hydrological years, oasis area, water-heat balance, oasis stability

Introduction

Natural oases form the basis for human production and living in arid areas. There are four main constraints for the formation of oases: flat and thick soil layers, relatively abundant water resources, high temperatures, and abundant sunshine [1, 2]. The former two are the necessary conditions for the formation of oases, while the latter two are the sufficient conditions. The continuous distribution of natural oases over a large area may be constrained by these conditions. However, as human activities become increasingly intense, the scale and spatial distribution of oases are affected by changes in the allocation, development, and utilization of water resources in basins. It is worth noting that in recent years, the desert-oasis transitional zone has gradually disappeared with oasis reclamation activities and water shortages, forming an ecological rift that

*e-mail: tangxia@llas.ac.cn

seriously threatens the stability of oases [3]. The limited water resources in arid areas can only support a certain scale of oases and transitional zones. Therefore, determination of the suitable scale of oasis development in a basin based on limited water resources is not only necessary to realize the rational allocation of water resources in arid areas but also a serious challenge facing the sustainable development of oases in arid areas [4].

Oasis stability is directly related to the sustainable development of the regional social economy. Oases that play a dual role in human activities and natural environmental changes have undergone complex evolution processes, especially in modern times, with the strengthening of the intensity of human activity and the increasing frequency of severe disruption of the natural water cycle and watershed transformation of the way oases evolve. Every change in the hydrological cycle drives a new round of oasis pattern adjustment. Oasis development may face the following realistic problems: the expansion of the scale of oases can threaten the natural environment; in particular, the irrational development and utilization of land resources can lead to desertification, salinization and soil quality degradation. The expansion of artificial oases can lead to competition with the development of natural oases for water resources. Are current oases stable in scale? These actual problems highlight the scientific issue and importance of this research, including how to select a typical oasis to determine the suitable scale to maintain the stable and sustainable development of oases.

To date, research on the suitable scale of oases in arid regions is relatively scarce. Most studies have focused on two aspects: the relationship between the cultivated area in oases and water resource consumption [5-7] and the land use/cover changes in arid regions that impact water resources [8-10]. Few studies have considered the suitable scale of oases in China or other countries, with water resources as the limiting factor. The first two models proposed were the water balance model [11, 12] and the water-soil balance model [13], which were used to estimate suitable scale of oases in the Hexi Corridor and on the southern margin of the Taklimakan Desert, respectively. Wang et al. [14] used the water and heat balance model to construct a green index to calculate the suitable scale of oases. With the deepening of studies on the suitable scale of oases, various factors, such as climate change [15], runoff variability [16-18], socioeconomic change [19], water-saving measures [20], ecological health [21], the proportions of natural oases and artificial oases [22], and ecological water demand [23, 24], have been applied in relevant models to estimate the suitable scale of oases with a greater precision. However, most studies have investigated the suitable scale of oases based on the mean annual runoff, and few studies have explored the suitable scale of oases for different hydrological years; consequently, the quantified suitable scale in these studies does not match the wet and dry cycles of water resources in the basins.

The Heihe River basin (HRB) is a representative basin for the evolution of inland oases and the utilization of water-soil resources in arid regions. The population density along the middle reaches of the HRB is high, accounting for over 90% of the total population in the basin, and its stability is directly related to the sustainable development of the economy, society and ecology in this basin. Population growth and socioeconomic development in this region have resulted in the overexploitation of water and land resources and a gradual decrease in the downstream flow, thereby leading to the deterioration of the ecological environment. To coordinate the water use conflicts in the HRB, the State Council of the People's Republic of China approved the Water Distribution Plan for the Main Stream of the Heihe River (97 Water Diversion Scheme, Shui Zheng Zi [1997] No. 496). The Yingluoxia Hydrological Station divides its upper and middle reaches, and the Zhengyixia Hydrological Station divides its middle reaches from its lower reaches. The 97 Water Diversion Scheme estimates the amount of water allocated from the Yingluoxia Hydrological Station to the Zhengyixia Hydrological Station corresponding to different probabilities of runoff. The rational use of the limited water resources to develop oases of suitable scales according to the 97 Water Diversion Scheme has become a challenge for the sustainable development of the middle reaches of the main stream Heihe River [25].

The oasis of the middle reaches of the Heihe River is an important ecological barrier in Northwest China. However, irrigation agriculture in the midstream region consumes approximately 65% of the river runoff, while over 90% of the irrigation water in the downstream region originates from groundwater [26]. Water is the key factor of oasis stabilization [21]. The agricultural oasis in the HRB expanded by 25.11% and 14.82% during the periods of 1986-2000 and 2000-2011, respectively, particularly in the counties of Shandan, Minle, and Jinta and the city of Jiuquan [27]. Therefore, in this study, we used the middle reaches of the main stream of the Heihe River as the study area and established a model based on the theory of water and heat balance to quantify the suitable scale of oases under different surface runoff scenarios, thus providing a scientific basis for the rational development of artificial oases according to water resources.

Material and Methods

Study Area

The Heihe River (37°45′-42°40′N, 96°42′-102°04′E) is the second largest inland river in China. The main stream of the Heihe River originates from the northern piedmont of the Qilian Mountains in Qinghai Province and ends at Juyan Lakes of Ejina Banner, Inner Mongolia, with a total length of approximately 821 km [28]. The HRB consists of 35 small tributaries, forming three independent sub-water systems in the east, middle and west. Among them, the eastern sub-water system is composed of the Liyuan River and 20 mountain tributaries extending east to the west from the Ciyaokou Reservoir in Shandan County to the Heidaban River in Gaotai County, with an area of 116,000 km^2 and a mean annual natural runoff of 2.475 billion m^3 [29]. In this study, the middle reaches of the main stream of the Heihe River refer to the eastern sub-water system of the HRB (Fig. 1), which flows through the main irrigated agricultural area in the oasis. The HRB land use and land cover dataset (HiWATER: Land cover map of Heihe River basin) was obtained from the Cold and Arid Regions Sciences Data Center (hppt://westdc.westgis.ac.cn/), and the landscape patches were classified into six types: forestland, grassland, cultivated land, water area, construction land and unused land.

Classification Criteria for Different Hydrologic Years

Based on the anomaly percentage P in the Standard for Hydrological Information and Hydrological Forecasting (GB/T22482-2008) [30], hydrological years were divided into three categories (high flow, normal flow and low flow) based on the amount of runoff in the basin (Table 1). The P values of the annual runoff in the middle reaches of the main stream of the Heihe River in 1954-2015 were calculated to classify years as high flow, normal flow, or low flow. In addition, the runoff variability (K) of each year was calculated, and the K series was used to reflect the trend of annual runoff to determine the K ranges corresponding to

Table 1 Grade of high-low flow.

Grade	Anomaly percentage *P*	The runoff modulus coefficient *K*
High-flow years	P>10%	K>1.1
Normal-flow years	-10%≤P≤10%	1.1≥K≥0.9
Low-flow years	P<-10%	K<0.9

the P values for the high-flow, normal-flow and low-flow years: P>10% represented a high-flow year (K>1.1), -10%≤P≤10% represented a normal-flow year (0.9≤K≤1.1), and P<−10% represented a low-flow year (K<0.9). Finally, the magnitude of runoff variability (K) was used to characterize the changes in the annual runoff in the middle reaches of the main stream of the Heihe River.

The Model for Estimating Available Water Resources in Oases

According to the water balance equation, the amount of water resources available in an oasis in the middle reaches of the Heihe River is expressed as

$$W_m = W_t - W_x - W_i - W_p \tag{1}$$

where W_m is the amount of water resources available in the oasis; W_t is the total amount of water resources that can be exploited; W_x is the total amount of industrial, agricultural, and domestic water use in the lower reaches of the HRB; W_i is the industrial water use in the middle reaches;

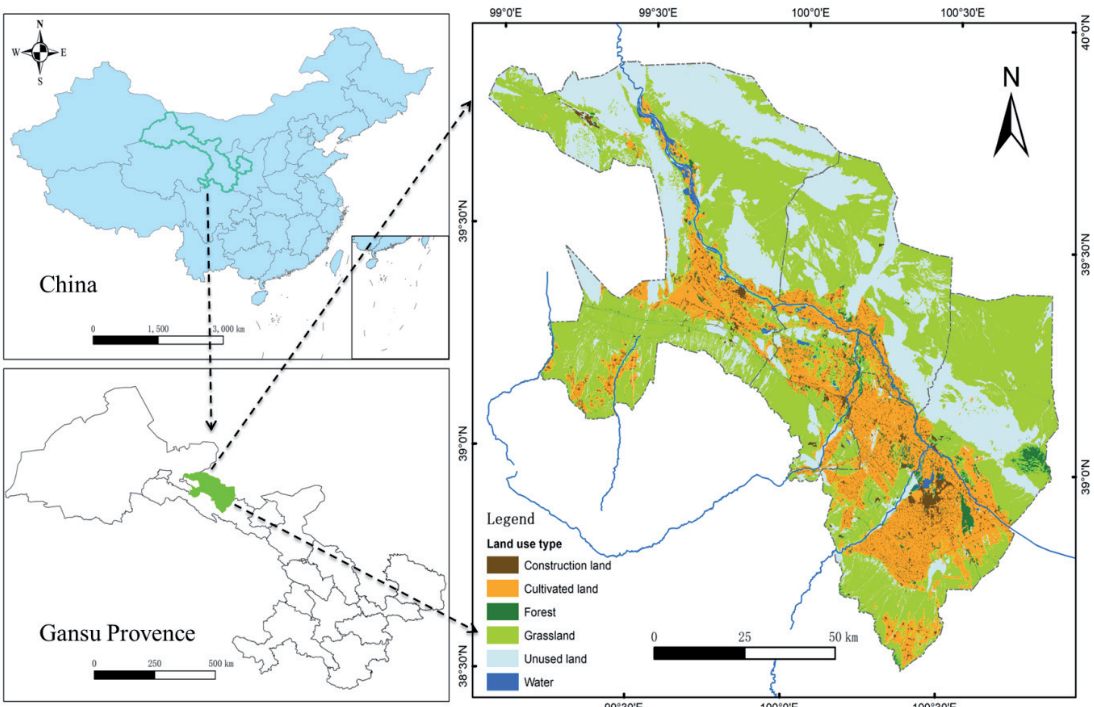

Fig. 1. Location of the middle reaches of the Heihe River Basin [21].

and W_p is the domestic water use in the middle reaches. The data on industrial, agricultural, and domestic water use in the lower reaches were obtained from the National Economic and Social Development Statistical Bulletin of Jiuquan City, Jinta County, Gansu Province and that of Ejina County, Inner Mongolia [21]. The data on industrial and domestic water use in the middle reaches were from the Zhangye City national economic and social development statistical bulletin of Gansu Province.

Construction of the Model of the Suitable Scale of Oases

The evolution of an oasis ecosystem depends on its water-heat balance [14]. Based on relevant research results [16, 21, 31], using ecological water-heat balance [14] and oasis circle theory [32], a suitable oasis scale model was developed. A model can be established to calculate the suitable scale of an oasis in the middle reaches of the main stream of the Heihe River under different inflow scenarios based on the concept. Therefore, the formula for calculating the suitable scale of oases is as follows:

$$A=\frac{Wm}{(ET_0-R)*k_p*H_0}\times 10^5 \quad (2)$$

where A is the scale of an oasis; Wm is the total amount of available water resources; ET_0 is the reference evapotranspiration calculated with the Penman formula; R is the annual mean precipitation in the basin; k_p is the comprehensive plant coefficient of the main vegetation in the oasis, which can be calculated as the weighted average of the plant coefficients of different types of vegetation, k_p = 0.7, 0.44, 0.90 for forestland, grassland and farmland, respectively [21]; and H_0 is the oasis stability index, which represents the extent to which the oasis is affected by the natural environment and artificial maintenance and disturbance.

In Formula 2, H_0 is obtained from the relative balance analysis of the actual water and heat conditions in the oasis region of the desert, which can reflect the stability of the oasis landscape from the perspective of the overall region. The greater the H_0 value is, the higher the stability of the oasis, and vice versa. H_0 can be used as an indicator to determine if an oasis is stable. Wang et al. [14] found, as shown in Table 2, that the stability of oases of a certain size can be determined and evaluated according to the range of H_0. The oasis is stable at H_0 = 0.75 and metastable at H_0 = 0.50.

Results

The Runoff in the Middle Reaches of the HRB Changed From 1954-2015

Water resources are the basis for the survival of oases in arid areas. The runoff data from 1954 to 2015 for the main stream of the Heihe River at the Yingluoxia Hydrological Station were used in this study to analyze the high-flow and low-flow cycles of the water resources in the middle reaches of the HRB. Fig. 2 clearly reflects the trend of runoff in the HRB. There were five normal-flow years and one high-flow year (1958) during this period of time. Most years from 1960-1980 were normal-flow and low-flow years. The years from 1975-1979 were normal-flow years. The runoff began to increase in the 1980s, and the period of 1981-1990 was characterized by cycles of normal-flow and high-flow years. In the 1990s, the interannual variation in the runoff in the basin was drastic, and the period of 2005-2013 became a high-flow period [19]. The mean annual runoff trend indicated that because the runoff in the middle reaches of the HRB was characterized by

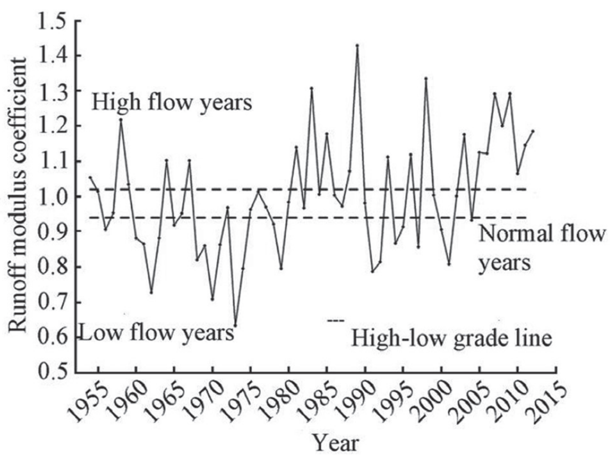

Fig. 2. High and low flow variations in the middle reaches of the Heihe River Basin.

Table 2. Stability division of an oasis [14].

Evaluation grade	H_0	Oasis Scale Evaluation
Unstable	<0.20	Take measures to save water or reduce the scale of artificial oasis to maintain the stability of the oasis
Metastable	0.20-0.50	No development potential
Stable	0.50-0.75	Under the protection of good measures, it has smaller development potential
Hyperstable	>0.75	With development potential, consider expanding the area of artificial oasis

apparent high-flow and low-flow cycles, determining the range of the suitable size of oases in the middle reaches of Heihe River according to the different runoff amounts into the basin is necessary.

The Amount of Exploitable Water Resources

There is no hydraulic connection between surface water and groundwater in the water system of the main stream of the Heihe River and in the water system of the Beida River, and the control area of the water system in the middle reaches of the HRB is essentially an independent hydrological unit. From 1954-2015, the mean annual runoff was 1.9422 billion m^3 for high-flow years, 1.5863 billion m^3 for normal-flow years, and 1.3127 billion m^3 for low-flow years. In addition, an additional 333 million m^3 of groundwater (not overlapping with surface water supply) in the main stream of the HRB and a total of 400.3 million m^3 of annual mean water resources in the mountain tributaries of the Heihe River, including the Shandan River, Hongshui River, Dazuma River, Liyuan River, and Bailang River, were observed [19]. In short, the total amount of exploitable water resources in the middle reaches of the HRB under different runoff conditions (not including the discharge from the Zhengyixia Hydrological Station) was 2.6755, 2.3196 and 2.0460 billion m^3 for high-flow years, normal-flow years and low-flow years, respectively.

Available Water Resources for the Oases

According to a study by Li et al. [33], the ecological water demand is 683 million m^3 to substantially control the degradation of the ecological environment in the lower reaches of the Heihe River, 801 million m^3 to preliminarily improve the ecological environment, and 927 million m^3 to significantly improve the ecological environment. This study assumes that the runoff during the high-flow, normal-flow, and low-flow years corresponds to the aforementioned three levels of ecological water demand in the lower reaches. The industrial, agricultural, and domestic water use in the town of Dingxin in Jinta County and Ejina Banner in the lower reaches totaled 152.5 million m^3. According to statistics from the city of Zhangye, industrial and domestic water use totaled 120 million m^3. Therefore, under the premise of preserving the ecological and environmental conditions downstream of the Heihe River, the total available water resources for the oases in the middle reaches are 1.455 billion m^3 for high-flow years, 1.225 billion m^3 for normal-flow years, and 1.069 billion m^3 for low-flow years according to Formula 1.

Changes in Artificial Oasis Area

The artificial oasis area increased by 117.46% from 1975 to 2015 in the middle reaches of the HRB (Fig. 3). From 1975 to 2000, the artificial oasis area increased

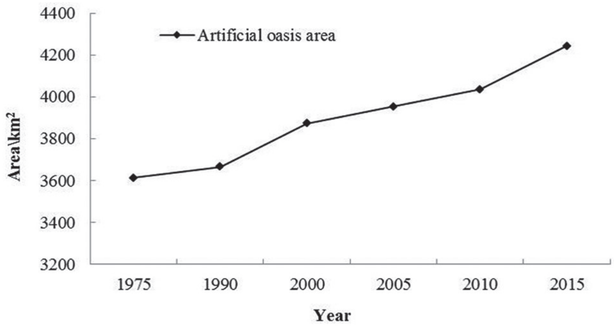

Fig. 3. Changes in the artificial oasis area of the middle reaches of the HRB.

at an average annual growth rate of 10.47 km^2. From 2000 to 2015, the artificial oasis area increased at an average annual growth rate of 24.59 km^2. The expansion of the artificial oasis area in the middle reaches of the basin will increase the demand for water resources, which will inevitably lead to a contradiction between the lower reaches of the basin supply of water resources; therefore, studying the appropriate scale of the oasis is necessary and urgent.

Suitable Scale of an Oasis

By comprehensively considering different runoff scenarios in the middle reaches of the Heihe River and ensuring sufficient flow in the lower reaches to achieve ecological and environmental restoration, the suitable scale of oases along the middle reaches and the stability of oases at the current scale were calculated according to Formula 2. The results are shown in Table 3.

According to Table 3, the suitable scale of oases along the main stream of the Heihe River in high-flow years is 3222-4832 km^2, while the actual oasis area and the oasis stability index in 2015 were 4242 km^2 and 0.57, respectively. The results indicate that under the premise of ensuring the water supply for the oases in the lower reaches, the quantity of water resources in the high-flow years can meet the production and domestic water consumption requirements in the oases along the middle reaches of the HRB, and oases developed at the modeled scale will be stable. However, the oasis stability index is 0.46 for normal-flow years and 0.39 for low-flow years, and the corresponding range of the suitable area of oases is 2583-3875 km^2 and 2221-3332 km^2, respectively, indicating the metastable status of oases in both normal-flow and low-flow years. The range of the suitable scale of oases determined in this study is essentially consistent with the results of the study by Hao and Su [19].

Discussion

The HRB oasis ecosystems support human civilization; however, the rapid expansion of artificial

Table 3. Stability and suitable scale of oases in the middle reaches of the Heihe River Basin.

Runoff level	Availability of water resources /10^8m^3	Reference crop evapotranspiration /mm	Precipitation /mm	Suitable scale of oasis/km^2		Status quo scale of oasis (2015)/ km^2	Suitability index of status quo scale (H_0)
				H_0 = 0.50	H_0 = 0.75		
High flow year	14.55	1042.70	130.40	4832.28	3221.52	4242	0.57
Normal flow year	12.25	1068.00	110.00	3874.55	2583.03	4242	0.46
Low flow year	10.69	1082.90	110.40	3331.93	2221.29	4242	0.39

oases has led to extremely limited water resources [34-36]. The runoff in the basin is mainly supplied by melting ice and snow from the upper reaches, and the limited water resources can only supply an area of oases at a certain scale. When the size of an oasis exceeds a suitable scale, many ecological problems occur, which restricts the sustainable development of the oasis [37, 38]. Only when the scale of the oasis is suitable can water and land resources be most effectively utilized to achieve a virtuous cycle of oasis development. If an oasis is too small, the land and water resources of the oasis cannot be fully utilized to develop the economy; if the oasis is overly large, the economic water use will cause a reduction in ecological water use, and the long-term sharp reduction in the environmental flow will eventually stifle the sustainable development of the oasis [23]. Due to the drying of the terminal lakes (such as the drying-up of Gaxun Nur in 1961 and Sogo Nur in 1992) [39], the government started to take action on water resource management to address the emerging issues. The water reallocation scheme was finally implemented in 2000 after it was successively proposed in 1992 and 1997, in which the midstream area should discharge 950 million m^3 (as measured at the Zhengyixia Hydrological Station) to downstream areas in normal years (when the upstream discharges 1580 million m^3 of water at Yingluoxia Hydrological Station) [36].

Previous studies have considered different aspects to maintain the stability of oases and promote the sustainable development of oases [40-43]. By considering the close relationship between the water consumption of an oasis and the scale of oases suitable for development, the oasis stability index H_0 was introduced to describe the ecological stability of the oasis based on different types of hydrological years and the concept of water resource-based land development [44]. H_0 is the "greenness" of the oasis under a certain water resource guarantee, which can reflect the degree of changes in the quantity of oasis water resources due to changes in the scale of oases and can be used as an index to determine is the oasis is stable [45,46]. This study showed that the oases along the middle reaches of the main stream of the Heihe River have H_0 values less than 0.5 in both normal-flow and low-flow years. In other words, they are metastable and do not have development potential, and a high input is likely necessary to maintain the current status of these oases.

The study of the area and stability of oases in the HRB is of great significance for solving the conflicts between water supply and demand and the development and protection of the ecological environment. According to the calculation of the water balance method, the area of the oases along the middle reaches of the HRB in 2015 far exceeded the suitable scale of oases that can be supported by the water resources in the basin in normal-flow and low-flow years. Therefore, to ensure the stability of the oasis system, it is necessary to take the following measures. 1) Strengthen the management of the oasis ecosystem, optimize the proportions of agriculture, forestry and animal husbandry based on local conditions, establish an effective and low-water-consumption shelterbelt system, continue to promote the construction of water-saving cities and society, and promote water-saving agricultural techniques [47]. 2) Adjust the planting structure to reduce the area of high-water-consuming crops, and improve the water-saving potential of the irrigation area to increase the efficiency of agricultural water use. 3) Scientifically regulate the surface runoff through the construction of water conservancy projects in the middle reaches. 4) Prohibit the overexploitation of groundwater resources in oases, and implement the joint scheduling and utilization of groundwater and surface water. Through the above measures, the area of the oases in the middle reaches should be controlled within a suitable range that can be supported by the available water resources instead of blindly developing and expanding artificial oases [48, 49].

Conclusion

(1) The runoff in the middle reaches of the HRB was characterized by apparent high-flow and low-flow cycles. The total quantity of water resources available for oases in the middle reaches was 1.455 billion m^3 in high-flow years, 1.225 billion m^3 in normal-flow years, and 1.069 billion m^3 in low-flow years.

(2) Under different runoff scenarios and under the premise of ensuring water availability for the ecological restoration target in the lower reaches, the suitable oasis areas in the middle reaches of the Heihe River were 3222-4832 km^2, 2583-3875 km^2, and 2221-3332 km^2 in high-flow, normal-flow, and low-flow years, respectively.

(3) The oasis area in 2015 was 4242 km^2, and the oasis stability index was 0.57 for high-flow years, 0.46 for normal-flow years, and 0.39 for low-flow years. These results indicate the stable status of oases in high-flow years and the metastable status of oases in both normal-flow and low-flow years.

Because of the complex ecological and hydrological processes of irrigated crops and natural vegetation along the middle reaches of the HRB, future research should consider how to determine the suitable proportions of arable land, woodland, and grassland in a stable oasis, how to calculate the suitable size of an oasis with the obtained proportions based on water conservation, a high efficiency and ecological health, and approaches for establishing a multibenefit oasis ecology protection system.

Author Contributions

Xia Tang analyzed the data, prepared the tables, reviewed drafts of the paper, and approved the final draft. Sen Li performed the experiments and helped draw the figures.

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Competing Interests

The authors declare that there are no competing interests.

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